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THE RELATIONSHIPS OF PHOSPHORUS AND NITROGEN TO THE TROPHIC STATE OF NORTHEAST AND NORTH-CENTRAL LAKES AND RESERVOIRS

Pacific Northwest Environmental Research Laboratory

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Data collected by the National Eutrophication Survey during 1972-73 from lakes and reservoirs in ten northeast and north-central states are presented. Relationships between total phosphorus concentrations and chlorophyll a, total phosphorus concentrations and secchi disc depth, total phosphorus concentrations and algal assay control yields are developed. Total annual phosphorus and nitrogen loadings to lakes are related to their trophic condition. Water quality criteria for phosphorus and nitrogen and also discussed.

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The Relationships of Phosphorus and Nitrogen to the Trophic State of Northeast and North-Central Lakes and Reservoirs

Working Paper No. 23

Preliminary Analysis of
National Eutrophication Survey Data
Collected During
the 1972-73 Sampling Period

National Eutrophication Survey
Pacific Northwest Environmental Research Laboratory, Corvallis, Oregon

December, 1974

INTRODUCTION

During the past 30 years, considerable effort has been spent by numerous investigators studying the various factors which are causing water bodies to become eutrophic. The preponderance of evidence indicates that controlling phosphorus is the single most important step that can be taken at the present time to alleviate nuisance conditions and other interferences with water uses caused by eutrophication of water bodies (Bartsch, 1972). One of the major questions to be answered in developing a eutrophication control program is "What phosphorus level is necessary to attain the desired trophic condition".

The question of nutrient levels both from the standpoint of "concentration" and "loading" is being addressed by the National Eutrophication Survey (NES). A review of the two approaches is presented in this report as well as the preliminary findings of the National Eutrophication Survey for lakes and reservoirs sampled in ten northeastern and north-central states (Connecticut, Maine, Massachusetts, Michigan, Minnesota, New Hampshire, New York, Rhode Island, Vermont and Wisconsin).

Within the past few years, there has been a controversy concerning the establishment of lake water quality criteria for phosphorus and whether or not they should be based on phosphorus concentrations within a lake or on phosphorus loading rates to a lake. The question of a single, nation-wide phosphorus criterion versus individually tailored

criteria for specific areas, or some compromise between the two, has also been discussed.

The concept of the concentration criteria is the older of the two, dating back primarily to Sawyer (1947) who suggested that concentrations at spring turnover of 0.010 mg/l of inorganic phosphorus and 0.300 mg/l of inorganic nitrogen were critical levels in the development of algal blooms. The concept of loading rate criteria stems largely from the work of Vollenweider (1968) who developed a relationship between annual nutrient loading rates and mean depth from which "permissible" and "dangerous" loading rates could be estimated for a lake with a given mean depth.

Vollenweider (1974) later refined his relationship to take into consideration the mean hydraulic retention time of lakes as well as the mean depth characteristic.

In 1968, the National Technical Advisory Committee Report recommended the following for plant nutrients and nuisance organisms:

> Recommendation: The Subcommittee wishes to stress that the concentrations set forth are suggested solely as guidelines and the maintenance of these may or may not prevent undesirable blooms. All the factors causing nuisance plant growths and the level of each which should not be exceeded are not known.
>
> (1) In order to limit nuisance growths, the addition of all organic wastes such as sewage, food processing, cannery, and industrial wastes containing nutrients, vitamins, trace elements, and growth stimulants should be carefully controlled. Furthermore, it should be pointed out that the addition of sulfates or manganese oxide to a lake should be limited if iron is present in the hypolimnion as they may increase the quantity of available phosphorus.

(2) Nothing should be added that causes an increased zone of anaerobic decomposition of a lake or reservoir.

(3) The naturally occurring ratios and amounts of nitrogen (particularly nitrate and ammonia) to total phosphorus should not be radically changed by the addition of materials. As a guideline, the concentrations of total phosphorus should not be increased to levels exceeding 100 µg/l in flowing streams or 50 µg/l where streams enter lakes or reservoirs.

(4) Because of our present limited knowledge of conditions promoting nuisance growth, we must have a biological monitoring program to determine the effectiveness of the control measure put into operation. A monitoring program can detect in their early stages the development of undesirable changes in amounts and kinds of rooted aquatics and the condition of algal growths. With periodic monitoring such undesirable trends can be detected and corrected by more stringent regulation of added organics.

The recommendation of the 1972 Water Quality Criteria Report of the National Academy of Science was as follows:

Recommendation: The principal recommendations for aesthetic and recreational uses of lakes, ponds, rivers, estuaries, and near-shore coastal waters are that these uses continue to be pleasing and undiminished by effects of cultural activities that increase plant nutrients. The trophic level and natural rate of eutrophication that exists, or would exist, in these waters in the absence of man's activities is considered the reference level and the commonly desirable level to be maintained. Such water should not have a demonstrable accelerated production of algae growth in excess of rates normally expected for the same type of water body in nature without man-made influences.

The concentrations of phosphorus and nitrogen mentioned in the text as leading to accelerated eutrophication were developed from the studies for certain aquatic systems: maintenance of lower concentrations may or may not prevent eutrophic conditions. All the factors causing nuisance plant growths and the level of each which should not be exceeded are not known. However, nuisance growths will be limited if the addition of all wastes such as sewage, food processing, cannery, and industrial wastes containing nutrients, vitamins, trace elements, and growth stimulants are carefully controlled and nothing is added that

causes a slow overall decrease of average dissolved oxygen concentration in the hypolimnion and an increase in the extent and duration of anaerobic conditions.

In the Proposed Criteria for Water Quality, October 1973, the Environmental Protection Agency presented the following:

Nutrient (Phosphorus)

No limit of acceptability is prescribed for phosphorus (P) in recreational waters.

Rationale (Phosphorus):

Acceptable limits for phosphorus in receiving waters where it is a limiting constituent for nuisance aquatic plant growths are believed to be:

Water Body	Maximum Phosphorus (P) Concentration
Within lakes and reservoirs	25 µg/l
At a point where a river enters a lake or reservoir	50 µg/l
Flowing streams	100 µg/l

Exceptions to the above, including a non-degradation clause, are further explained in the text of the proposed criteria.

CONCENTRATION APPROACH

Dillon and Rigler (1974), expanding on the work of Sakamoto (1966) related total phosphorus concentration at spring overturn to summer chlorophyll a concentrations (Figure 1) for lakes having a nitrogen to phosphorus ratio of greater than 12, i.e., phosphorus limited. A regression

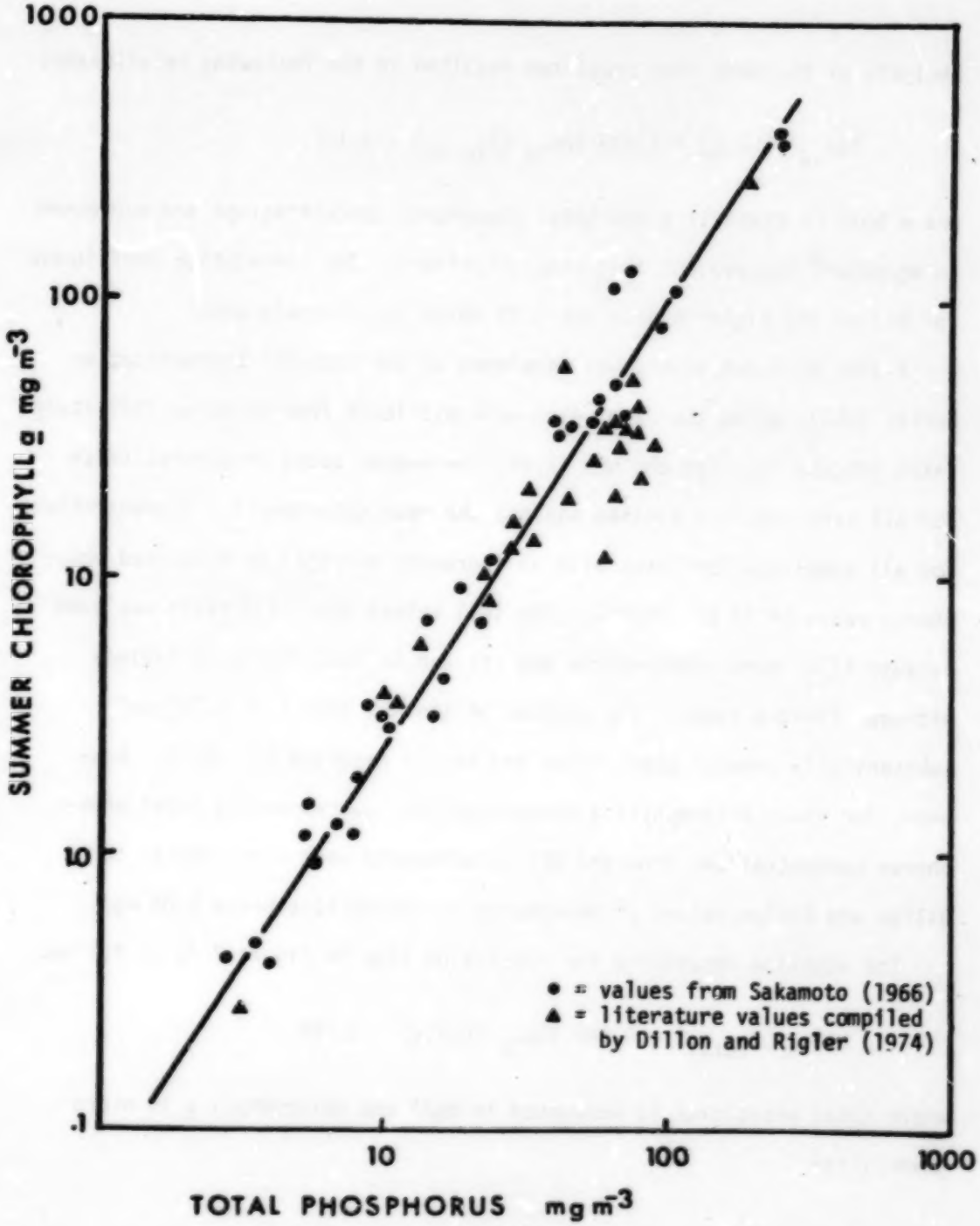

Figure 1 The Relationship of Summer Average Chlorophyll to Spring Total Phosphorus (Dillon and Rigler, 1974)

analysis of the data they presented resulted in the following relationship:

$$\log_{10} [\text{Chl } \underline{a}] = 1.449 \log_{10} [P_{total}] - 1.136$$

where both chlorophyll a and total phosphorus concentrations are expressed in mg/meter^3 (equivalent to micrograms/liter). The correlation coefficient for Dillon and Rigler's data was 0.95 which is extremely good.

A similar relationship was developed by the National Eutrophication Survey (NES), using the data which were available from selected 1972 study lakes (Figure 2). For the NES lakes, the median total phosphorus value for all samplings was plotted against the mean chlorophyll a concentration for all samplings for lakes with an inorganic nitrogen to dissolved phosphorus ratio of 14 or greater. The 14:1 rather than 12:1 ratio was used because it is more conservative and its use is less likely to include nitrogen limited lakes. The scatter of the NES data ($r = 0.78$) was substantially greater than Dillon and Rigler reported ($r = 0.95$); however, for given chlorophyll a concentrations, corresponding total phosphorus concentrations from the NES relationship were very similar to Dillon and Rigler values at phosphorus concentrations below 0.05 mg/l.

The equation describing the regression line in Figure 2 is as follows:

$$\text{Log}_{10} [P_{total}] = 0.846 \log_{10} [\text{Chl } \underline{a}] - 2.354$$

where total phosphorus is expressed in mg/l and chlorophyll a in micrograms/liter.

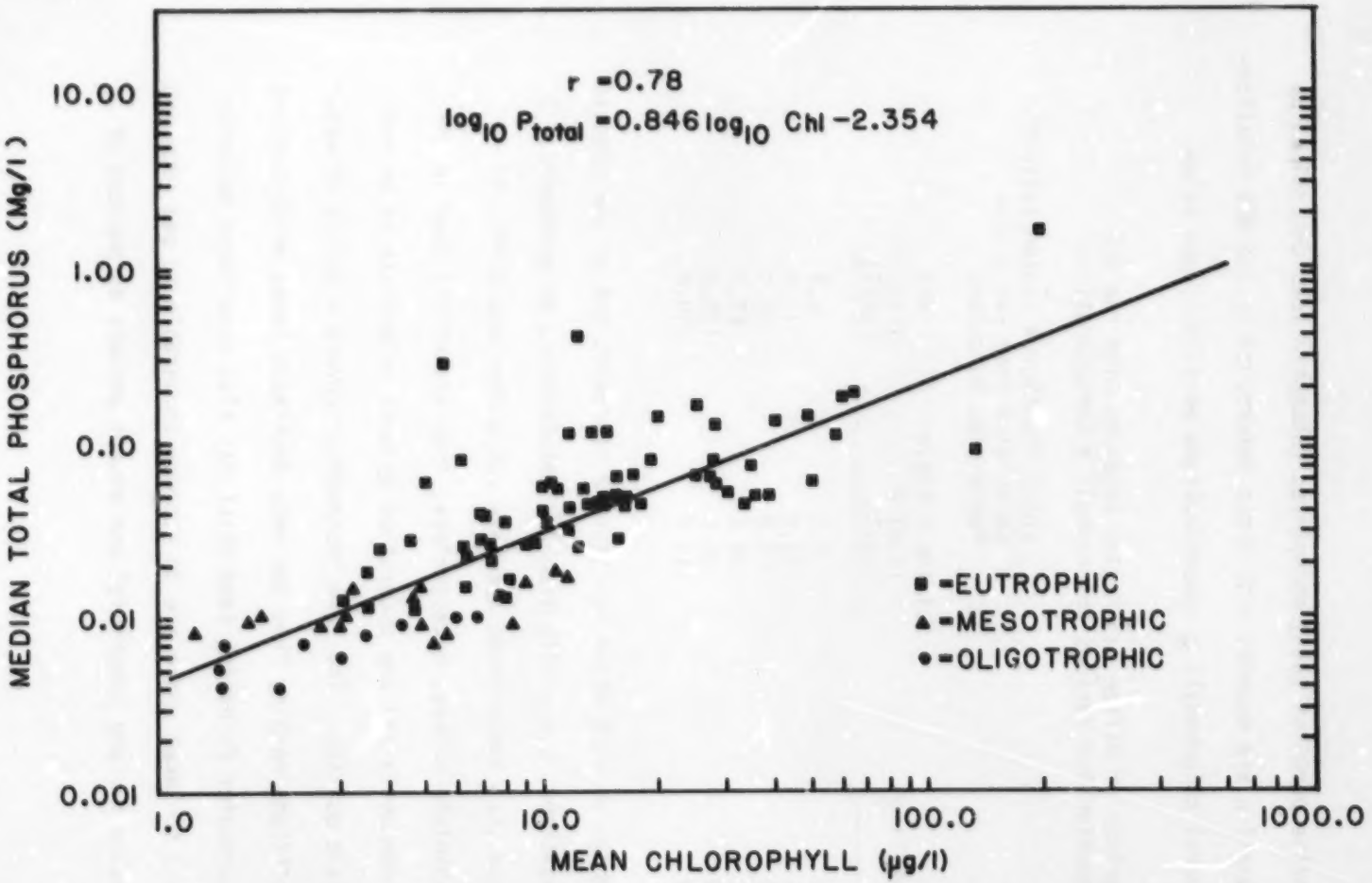

FIGURE 2 THE RELATIONSHIP BETWEEN MEDIAN TOTAL PHOSPHORUS AND MEAN CHLOROPHYLL a IN PHOSPHORUS LIMITED LAKES

For comparative purposes total phosphorus concentrations determined by Dillon's equation are equated with those determined by the NES relationship at several chlorophyll a concentrations as illustrated below.

Comparison of Dillon and Rigler Equation with the NES Equation for Various Chlorophyll a Concentrations

Chlorophyll a (µg/l)	Total Phosphorus Concentrations Calculated from Respective Regression Equations	
	Dillon & Rigler Total P (µg/l)	NES Total P (µg/l)
1	6.1	4.4
5	18.4	17.4
10	29.8	30.9
25	56.2	67.9
50	90.6	120.0
100	145.9	219.0

The symbols on each point in Figure 2 represent one of the classic trophic conditions, i.e., oligotrophic, mesotrophic, or eutrophic. It is recognized that these terms are very subjective and difficult to define in absolute values, nevertheless, they are widely used in the scientific community and are understood by most scientists to be indicators of lake quality. The term "eutrophic" covers a myriad of water quality conditions ranging from the very desirable lakes which support excellent warmwater fisheries (and which may also experience nuisance algal blooms) to lakes which are in essence comparable to pea soup and are of no value for any beneficial use except perhaps as sources of

irrigation water. Oligotrophic and mesotrophic lakes are generally considered to be free of nuisance phytoplankton blooms and specifically of blue-green algae nuisances.

The NES staff assigned trophic conditions to each of the lakes represented in Figure 2 based on pertinent chemical, biological, and physical data collected by the Survey, data available from state agencies or other sources, and frequently including communication with state personnel who had personal knowledge of the lake in question.

Several observations can be made concerning the relationships in Figure 2. Those lakes classified as oligotrophic did not exceed a median total phosphorus concentration of 10 µg/l or a mean chlorophyll a concentration of 7 µg/l. Median total phosphorus concentrations in the mesotrophic lakes did not exceed 18 µg/l and chlorophyll a means did not exceed 12 µg/l. The majority, but not all, of the eutrophic lakes had median total phosphorus concentrations greater than 18 µg/l.

These observations relating trophic condition to total phosphorus and chlorophyll a levels fit reasonably well with chlorophyll a ranges, corresponding to the various trophic conditions, suggested by others (Sakamoto, 1966; National Academy of Sciences, 1972; Dobson et al., 1974) as indicated below:

	Chlorophyll a (µg/l)			
Trophic Condition	Sakamoto	Academy	Dobson	Survey
Oligotrophic	0.3-2.5	0-4	0-4.3	<7
Mesotrophic	1-15	4-10	4.3-8.8	7-12
Eutrophic	5-140	>10	>8.8	>12

On the basis of the Survey's chlorophyll a to total phosphorus relationship and the chlorophyll a range give by the National Academy of Sciences, the following phosphorus guidelines would be suggested:

Trophic State	Chlorophyll a (µg/l)	Total Phosphorus (µg/l)
Oligotrophic	<4	<14
Mesotrophic	4-10	15-30
Eutrophic	>10	>30

If a phosphorus guideline were established empirically on the basis of the data presented in Figure 2, the following would be concluded:

Trophic State	Chlorophyll a (µg/l)	Total Phosphorus (µg/l)
Oligotrophic	<7	<10
Mesotrophic	7-12	10-20
Eutrophic	>12	>20

It should be noted that the suggested guidelines presented above and, in fact, in the remainder of this report, apply only to those water bodies where phytoplankton and not aquatic macrophytes dominate primary production.

Figure 3 represents the relationship between median total phosphorus and mean Secchi disc depths for those lakes with an inorganic nitrogen: dissolved phosphorus ratio greater than 14. The correlation coefficient for this relationship was -0.82 and the line of best fit is described by the following equation:

$$\log_{10} (P_{total}) = -1.307 (\log_{10} \text{Secchi}) + 0.818$$

where the units of total phosphorus are mg/l and Secchi disc depth units are inches.

Empirically, these data suggest that mean Secchi disc depth in mesotrophic lakes will exceed 78 inches (2 meters) and in oligotrophic lakes, 144 inches (3.7 meters), as indicated in the table below. One oligotrophic lake plotted in Figure 3 had a mean Secchi disc depth of less than 3.7 meters; however, the value did not represent the maximum transparency because on at least one occasion, the Secchi disc was resting on the lake bed when the reading was made (Thomas, 1974).

Trophic State	Secchi Disc Depth
Oligotrophic	>12.1 feet (3.7 meters)
Mesotrophic	>6.6 feet (2.0 meters)
Eutrophic	<6.6 feet (2.0 meters)

The suggested guidelines for Secchi disc depths corresponding to the three major trophic conditions are somewhat lower than would be expected, based on literature values. Lueschow, et al. (1970), who reported on studies of 12 Wisconsin lakes, stated that lakes with mean Secchi disc depth greater than 12 feet (3.7 meters) experienced no deterioration of recreation potential due to plankton growths. This Secchi disc depth corresponds to the NES assigned oligotrophic condition and a total phosphorus concentration of 10 µg/l or less.

In the Proposed Criteria for Water Quality, October, 1973, EPA suggested a minimum water transparency of 4 feet (1.2 meters) for bathing

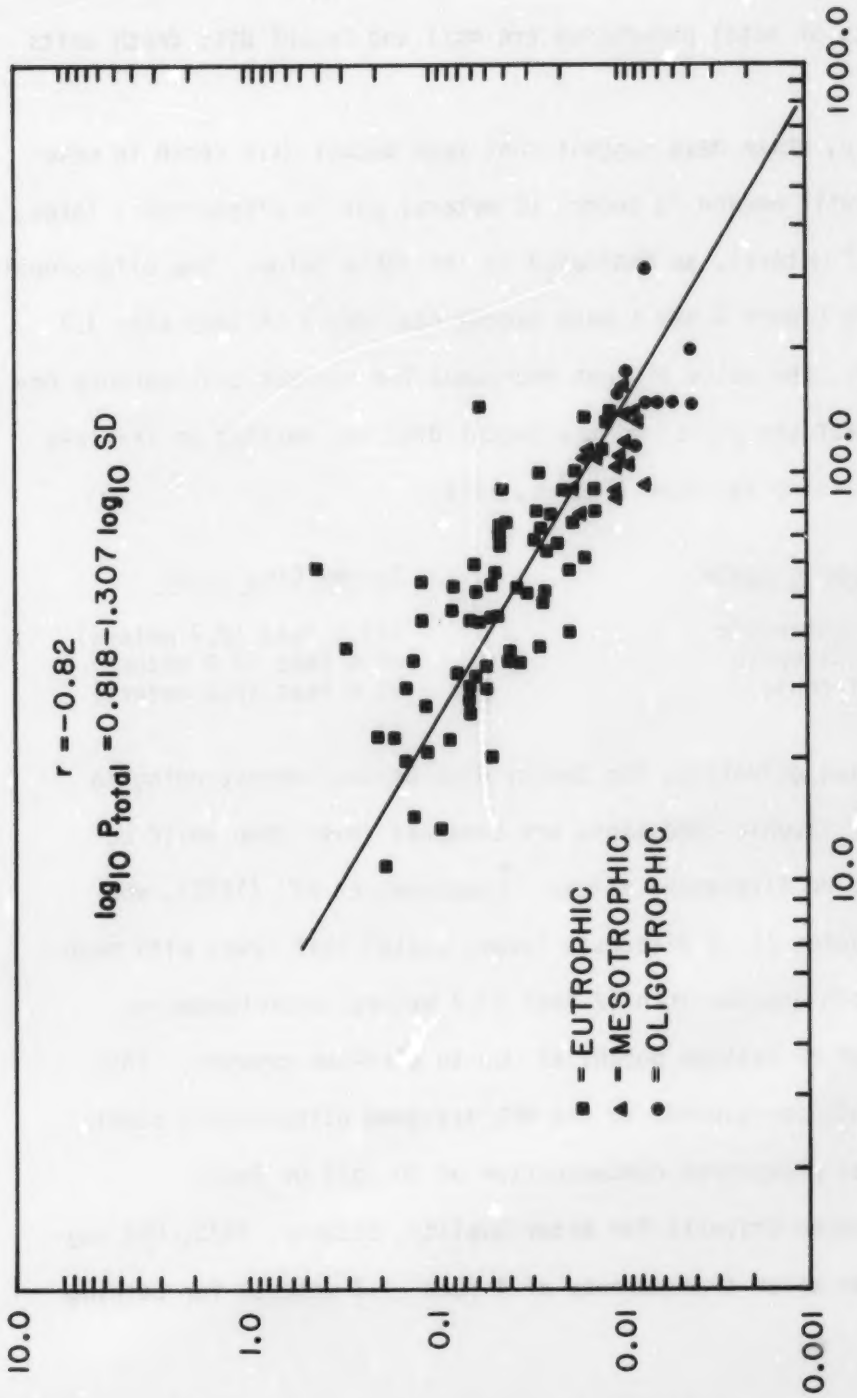

FIGURE 3 THE RELATIONSHIP BETWEEN MEDIAN TOTAL PHOSPHORUS AND MEAN SECCHI DISC DEPTHS IN PHOSPHORUS LIMITED LAKES

areas. Using the NES regression equation, this transparency corresponds to a total phosphorus concentration of 42 µg/l which represents a very enriched condition and is therefore not suggested as a desirable guideline for total phosphorus.

The relationship between the control algal assay yield and the median fall total phosphorus concentration is depicted by Figure 4. The regression line for this relationship is:

$$\log_{10} (P_{total}) = 0.419 \log_{10} (\text{AA Yield}) - 1.603$$

where total phosphorus and algal assay yield are expressed in mg/l. All of the oligotrophic and mesotrophic lakes except one (Lake Champlain) had control yields of 0.9 mg/l dry weight or less. Based on the regression line, a yield of 0.9 mg/l corresponds to a median fall phosphorus concentration of 25 µg/liter, which fits well with the phosphorus guidelines suggested by the previously discussed relationships.

Miller, Maloney, and Greene (1974) assigned four levels of productivity to algal assay control yields in their study of 49 U.S. lakes, including a range from 0.1 mg/l to 0.8 mg/l which they described as moderate productivity and which corresponded to mesotrophic conditions. Their data agree with the Survey observations.

As determined by the algal assay procedure, about 57% of all the lakes sampled in 1972 were phosphorus limited, while 37% were limited by nitrogen, 1% were limited by an unidentified element and the data were not conclusive for the other 5% of the lakes.

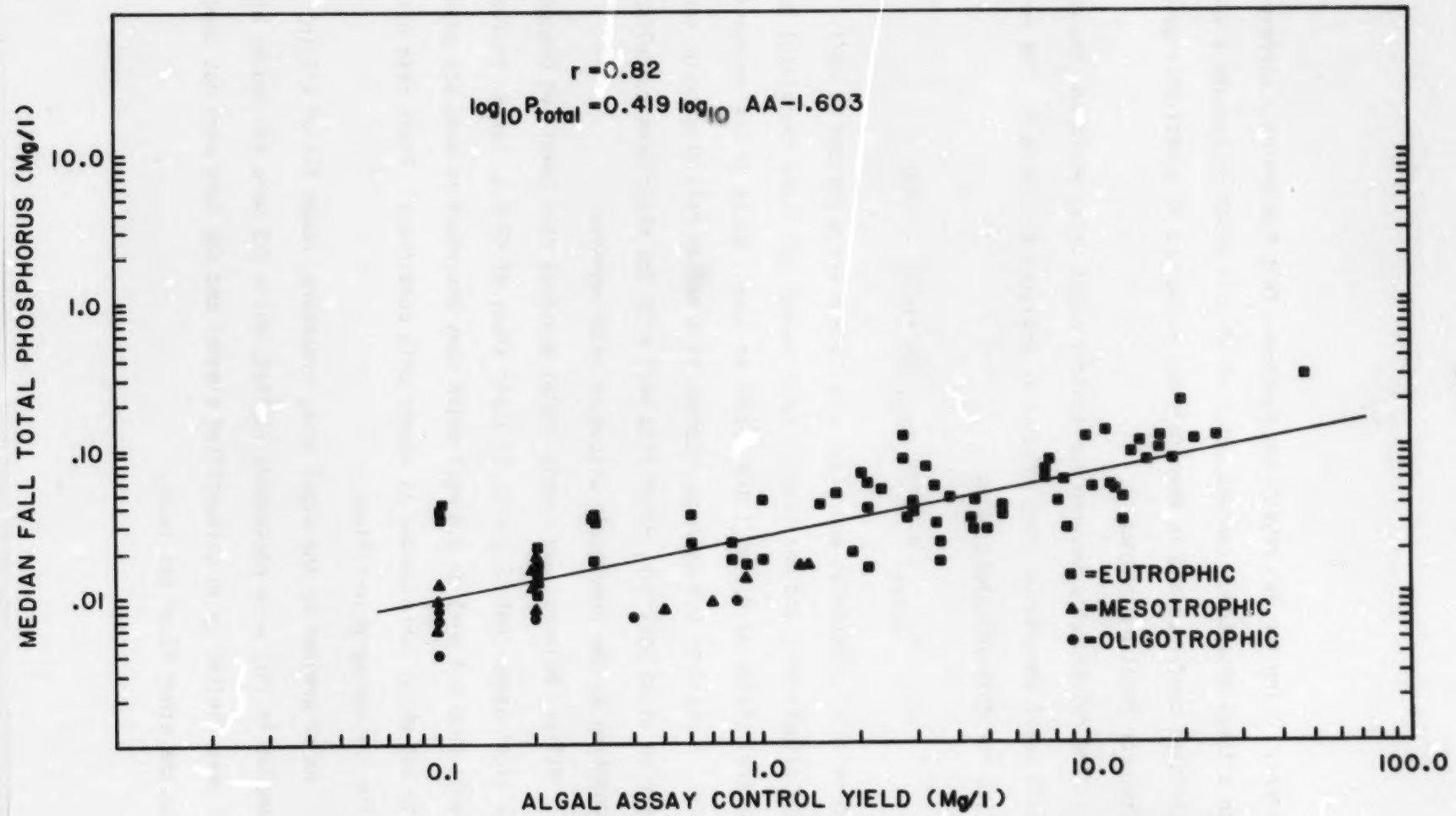

FIGURE 4 THE RELATIONSHIP BETWEEN MEDIAN TOTAL PHOSPHORUS DURING THE FALL SAMPLING AND ALGAL ASSAY CONTROL YIELDS

In summary, suggested guidelines for total phosphorus as determined by concentration approach ranged from 20-30 µg/l using the various chlorophyll a relationships. Depending on whether the Leuchow, et al. recommendation of a minimum 12 foot Secchi disc reading to maintain nuisance-free conditions or the proposed Water Quality Criteria's recommendation of a minimum 4-foot Secchi disc reading for bathing areas is used, a total phosphorus guideline of 10 to 40 µg/l would be suggested. The algal assay relationship on the other hand, suggests a total phosphorus guideline of 25 µg/l.

The above guidelines, based on this preliminary analysis of the data, generally support the Proposed Water Quality Criteria of 25 µg/l as a level which should not be exceeded in lakes or reservoirs to maintain conditions free of nuisance blooms.

Summary data, from which the points on Figures 2 through 4 were derived, are presented in Appendix A to this report.

LOADING APPROACH

The first attempt to unify the nutrient loading concept with the trophic condition of lakes was made by Vollenweider in 1968. He related total phosphorus loadings (g/m^2 lake surface area/year) to the mean depths of lakes and then empirically determined the loading rates corresponding to the three classical trophic conditions; oligotrophic, mesotrophic and eutrophic. A similar relationship was derived for nitrogen loading, assuming that algal nitrogen requirements were related to phosphorus requirements in the ratio of 15:1.

In order to account for large differences in flushing rates of lakes, Vollenweider (1973) later modified his relationship by plotting total phosphorus load ($g/m^2/yr$) against the ratio of mean depth to mean hydraulic detention time. This modification was based on a theoretical input-output model which he had also developed.

Using Vollenweider's newest relationship, preliminary data from the Survey for selected phosphorus limited lakes were graphed as illustrated in Figure 5.

The lines in Figure 5 correspond to Vollenweider's empirical permissible and critical loading rates which, in effect, are observed limits between for oligotrophic-mesotrophic and mesotrophic-eutrophic lakes.

In general, Figure 5 indicates that the Vollenweider loading concept holds true when tested with Survey data although there were exceptions and also a scarcity of lakes included in the Survey which had low mean depth to detention time ratios, were eutrophic, and phosphorus limited.

At least two of the lakes or reservoirs which were eutrophic and had phosphorus loadings less than the critical loading were dominated by aquatic macrophytes rather than phytoplankton.

The two mesotrophic lakes which exceed the critical loading are very deep and therefore have a large assimilative capacity. Green Lake (Wisconsin) has a mean depth of 32 meters and Cayuga Lake (New York) has a mean depth of 52 meters. Conceivably, neither of these lakes may have achieved a trophic condition in equilibrium with the phosphorus input. Both lakes receive heavy nutrient loads from municipal sewage treatment plants.

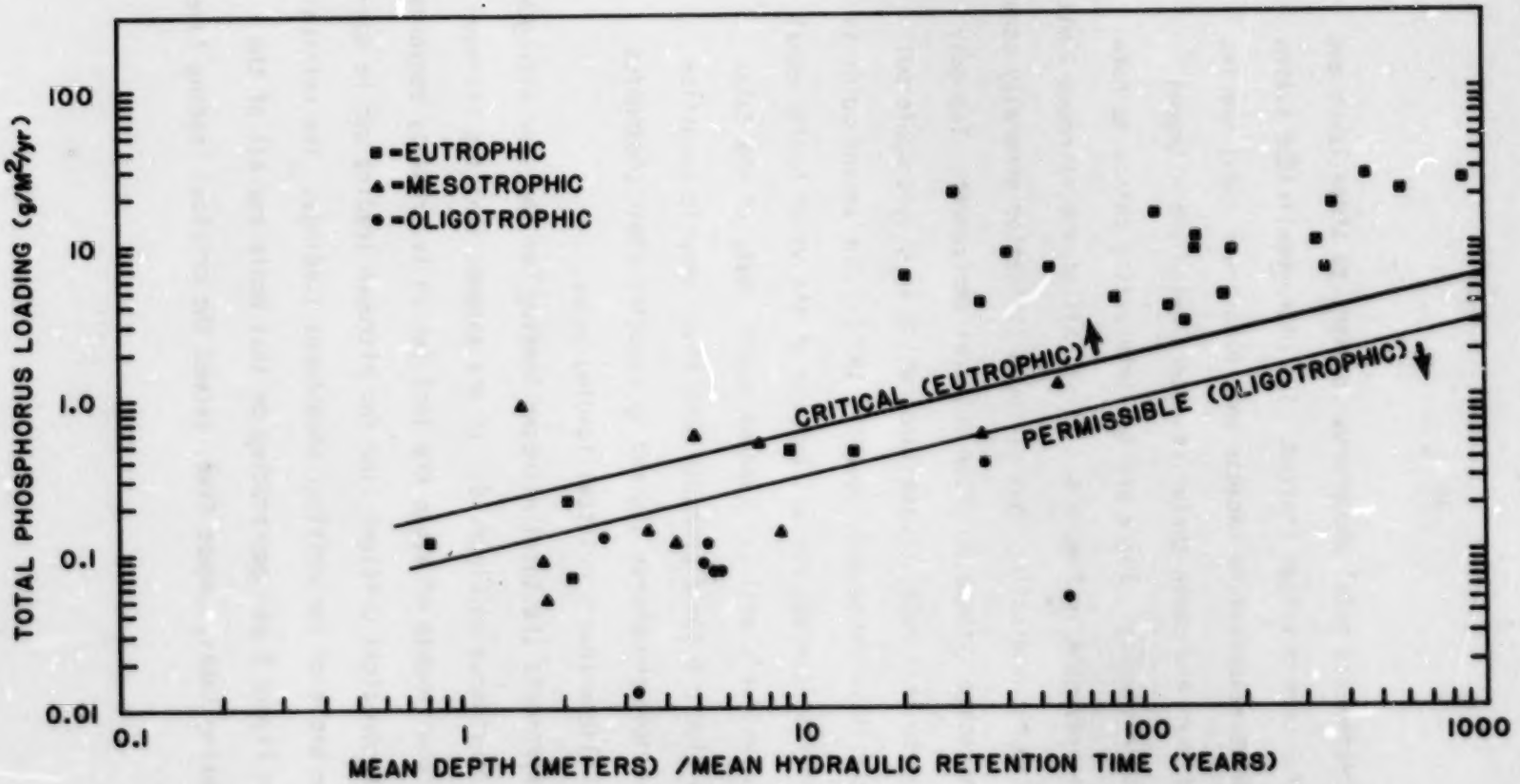

FIGURE 5 THE RELATIONSHIP OF TOTAL PHOSPHORUS LOADING AND LAKE MORPHOMETRY TO TROPHIC CONDITION OF PHOSPHORUS LIMITED LAKES

Figure 6 represents total phosphorus loadings to those lakes and reservoirs which were nitrogen limited. The nitrogen-limited status was assigned with reservations because some blue-green algal species are nitrogen-fixers and could thrive in waters which are nitrogen limited for other species. There are two interesting points to note about the data presented in Figure 6. First, all of the nitrogen-limited lakes were eutrophic indicating that nitrogen limitation generally occurs only in very enriched systems or after cultural enrichment. The only known exception to this rule is Lake Tahoe which is oligotrophic but nitrogen-limited (Lake Tahoe Area Council, 1971). The second point is that the phosphorus loadings for all but six of the water bodies equal or exceed Vollenweider's critical loading level. Many of the lakes represented in Figure 6 could probably have their trophic condition improved and be made phosphorus limited by reducing their phosphorus loading below Vollenweider's critical loading value.

Figure 7 represents the total nitrogen loading for the same nitrogen-limited lakes considered in Figure 6. If one assumes that the nitrogen to phosphorus requirements of algae are 14:1 (which is probably conservative), then a theoretical critical line for nitrogen loading can be constructed on the basis of the critical phosphorus loadings. The critical loading line in Figure 6 was constructed on that basis and all of the points representing lakes, except five, exceed the critical loading level for nitrogen.

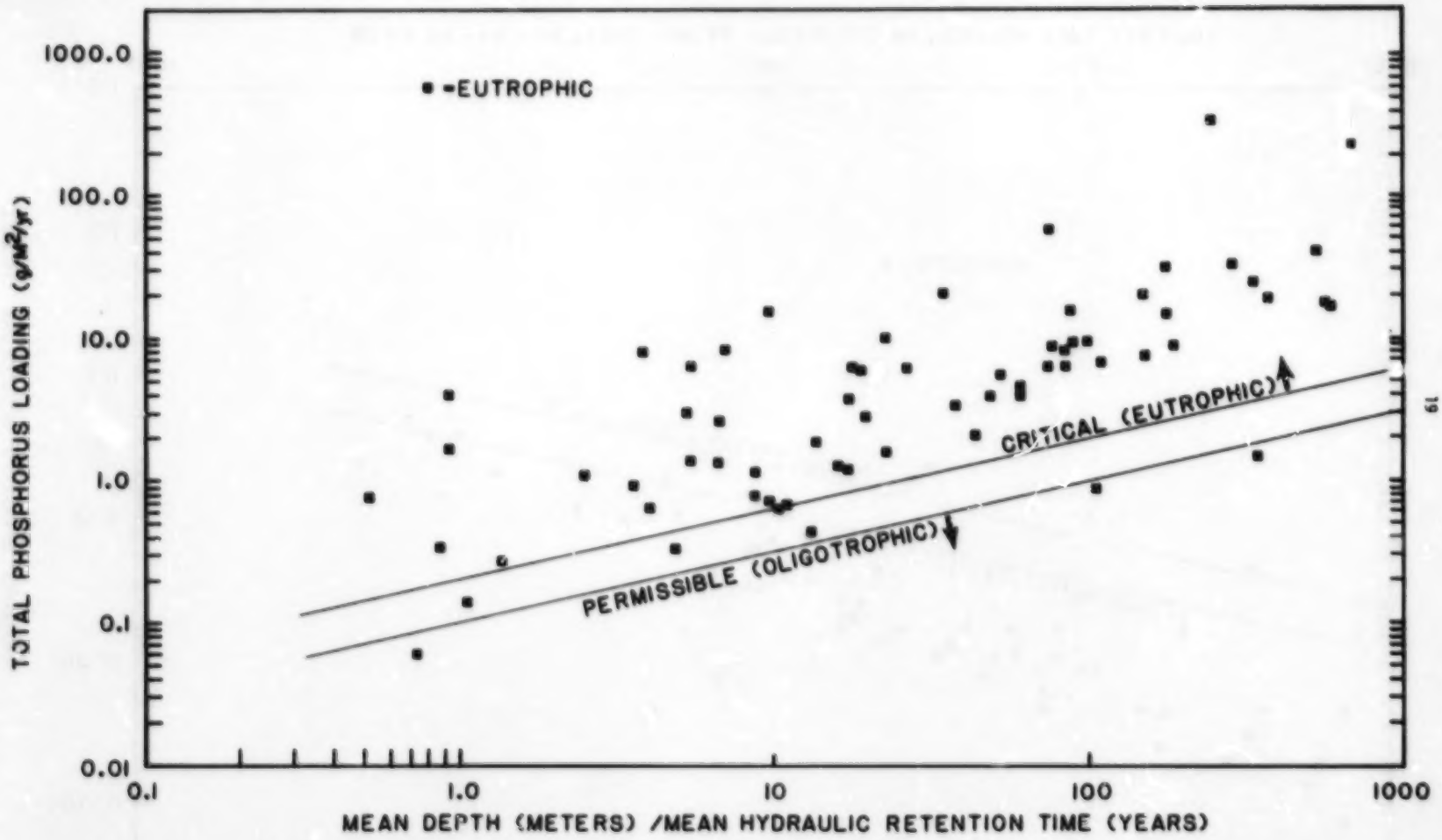

FIGURE 6 THE RELATIONSHIP OF TOTAL PHOSPHORUS LOADING AND LAKE MORPHOMETRY TO THE TROPHIC CONDITION OF NITROGEN LIMITED LAKES

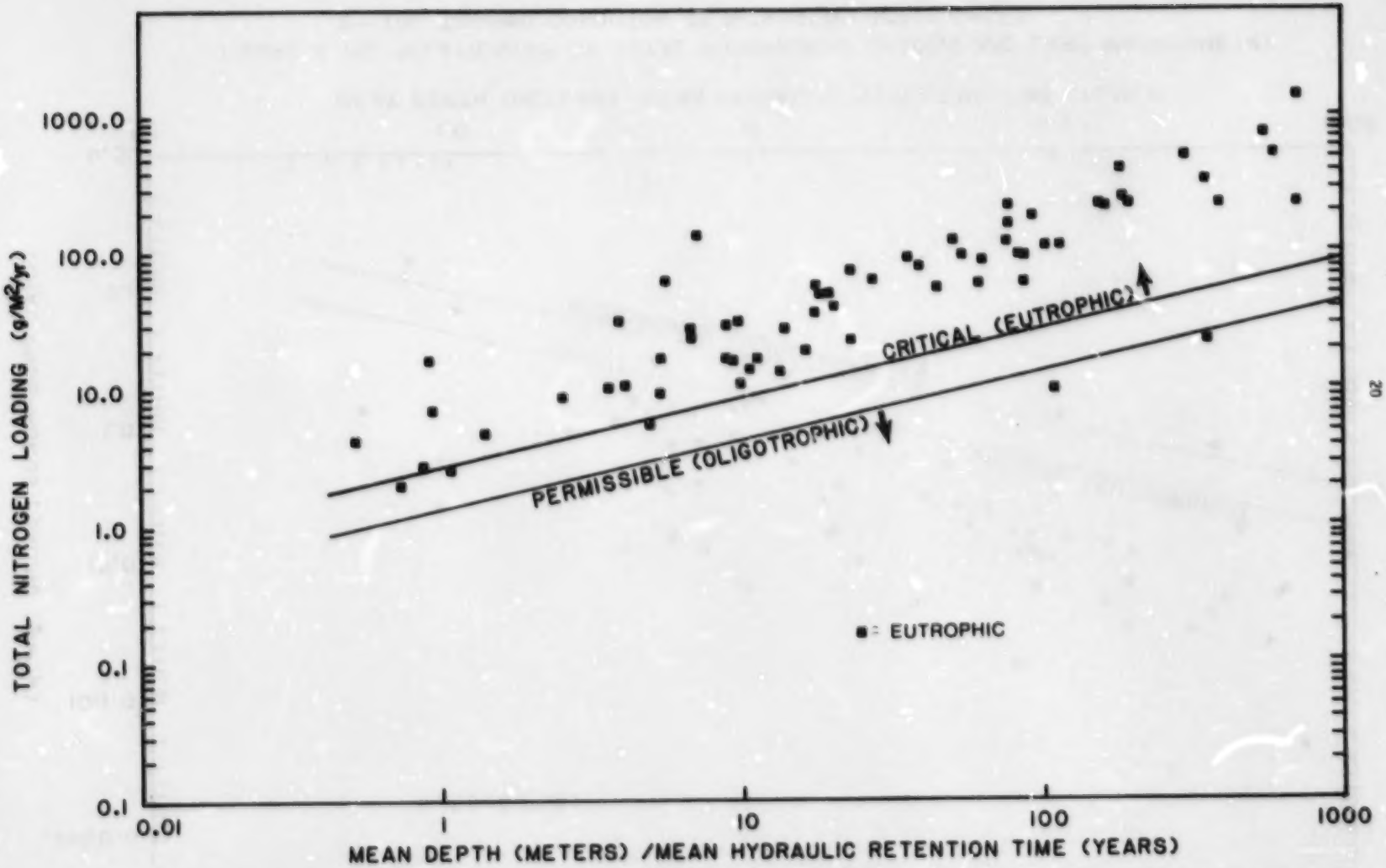

FIGURE 7 THE RELATIONSHIP OF TOTAL NITROGEN LOADING AND LAKE MORPHOMETRY TO TROPHIC CONDITION OF NITROGEN LIMITED LAKES

It is not suggested that a water quality criteria or guideline for nitrogen be formulated for wide application. Nitrogen is not as controllable material, like phosphorus and is generally available in large quantities to aquatic systems from a variety of diffuse sources including land runoff, precipitation and nitrogen fixation. The formulation and widespread application of a criterion or guideline for nitrogen would only serve to confuse and detract from the main issue which should be phosphorus control in the majority of cases.

A relationship like Figure 7, however, might be useful in special cases such as Lake Tahoe. One other point of interest in Figure 7 is the apparent linearity of the relationship between nitrogen loadings and the mean depth to detention time ratio. The phenomenon does not have any great significance to the criteria issue but is explained by the fact that, generally, as the mean depth to detention time ratio increases so does the drainage area to surface area ratio. Since nitrogen export per unit of drainage area is relatively constant, total nitrogen load increases proportionally with drainage area size without appreciable scattering. These factors in combination tend to produce the linear relationship observed in Figure 7.

Summary data from which the points on Figures 5 through 7 were derived are presented in Appendix B to this report.

DISCUSSION

Two concepts of developing phosphorus criteria for controlling eutrophication in lakes and impoundments have been presented. From a management viewpoint, a loading rate criteria would be easier to work with than lake concentration criteria because the former is one step closer to the source of nutrient supply; therefore, once a desirable loading rate to a given water body is established, it would be relatively easy to determine the extent of phosphorus reduction from point sources and non-point sources necessary to achieve the desired loading.

On the other hand, if a concentration criterion alone were applied to a water body, the back calculation necessary to determine the phosphorus reduction necessary to meet that concentration level would be much more difficult because the relationship between concentration in a lake and loading to a lake is complex. Factors such as volume, detention time, mixing patterns, biological activity, sedimentation rates and resolubilization of phosphorus from the sediments all play a role in determining the concentration that will result from a given loading rate.

A single loading rate criterion for a lake also has disadvantages because it is applied with the assumption that the loading is equally distributed to all parts of the lake. This assumption is often invalid particularly in larger lakes or reservoirs with several tributary streams each carrying different nutrient loads. While the average loading rate to the entire lake may appear acceptable, phosphorus loads in some embayments may be excessively high, resulting in localized nuisance problems,

while other areas may receive very light phosphorus loads and have no problems.

Both the loading and concentration concepts, as presented, were not without exceptions, some of which could be explained and some with no apparent explanation; however, exceptions are to be expected when working with ecological systems.

This report has dealt primarily with the question of setting a phosphorus guideline or criterion (loading, concentration, or a combination of the two) which, if not exceeded, promises a high probability of avoiding nuisance phytoplankton blooms. It has not addressed the question of what phosphorus loadings or concentrations are achievable or desirable for water bodies in different geographical or geological areas, land use types, climates, etc.

While one might expect to find a large number of oligotrophic lakes in Maine or Upper New York, oligotrophic lakes through the nutrient-rich mid-west would be a rarity even without cultural influences. In some areas, natural phosphorus inputs may be sufficiently great to produce occasional or frequent phytoplankton blooms which interfere with one or more lake uses.

It would seem logical that numbers such as those presented in this report could be offered as guidelines which should be followed to achieve high quality lakes and reservoirs relatively free of nuisance bloom conditions. For enforcement purposes, however, criteria for phosphorus should be based on the lowest achievable background given the geology, land use,

drainage area size, lake morphometry, and other unique factors in each specific case. Either the concentration or loading approach could be used in applying such criteria and variances from the lowest achievable background should be made for specific cases where higher productivity levels are desired.

A report on additional Survey data investigating the relationship between land use and other factors influencing nutrient export is being prepared and should be useful in the further development of this concept.

It should be noted that the data presented in this report represent only the majority of the information available from the Survey's first year of effort in ten northeast and north-central states. As data from the southeast, midwest, and western states become available, they will be treated in a similar manner and, in addition, new relationships will be tested as patterns develop.

SUMMARY AND CONCLUSIONS

Based on preliminary analysis of the data from the first year of the National Eutrophication Survey, the following statements can be made:

1. A general relationship was described between median total phosphorus concentrations and chlorophyll a in phosphorus limited lakes. Although more scatter was noted in the Survey data, the relationship fitted very well with data previously presented by Sakamoto (1966) and Dillon and Rigler (1974).

2. Using the phosphorus-chlorophyll a relationship, several approaches can be used to suggest phosphorus guidelines to avoid nuisance phytoplankton blooms. Phosphorus guidelines determined in this manner ranged from 20-30 µg/l total phosphorus.

3. The Survey data indicated that all of the oligotrophic and mesotrophic lakes had mean chlorophyll a concentrations less than 12 µg/l.

4. A general relationship was described between median total phosphorus concentrations and Secchi disc readings which empirically suggested that, in general, Secchi disc readings in eutrophic lakes are less than 2 meters. Based on the minimum transparency of 4 feet (1.2 meters) for bathing areas recommended by the EPA Proposed Criteria for Water Quality, a phosphorus guideline of 42 µg/l total phosphorus could be proposed, although this concentration corresponds to well eutrophied water which would probably be objectionable for other reasons.

5. Survey data suggested that oligotrophic lakes have Secchi disc readings greater than 11.8 feet (3.6 meters) and mesotrophic lakes greater than 6.6 feet (2.0 meters). These values, however, seem low when compared to those proposed by others.

6. A general relationship was described between median fall total phosphorus concentrations and control algal assay yield which empirically suggested a total phosphorus guideline of 25 µg/l to maintain nuisance-free conditions.

7. The guideline for total phosphorus concentrations, suggested by the relationships developed in this report, generally support the concentration of 25 µg/l suggested in the "Proposed Water Quality Criteria" as a level which should not be exceeded in lakes or reservoirs to maintain conditions free of nuisance blooms.

8. Vollenweider's loading approach, on the basis of Survey data, is a viable mechanism for establishing total phosphorus loading guidelines for lakes and reservoirs which are phosphorus limited or can be made phosphorus limited. Loading limits are established specifically for each lake based on its mean depth and mean hydraulic retention time characteristics.

9. Using the Vollenweider concept, a similar relationship can be developed for deriving total nitrogen loading guidelines for nitrogen-limited lakes.

10. All of the nitrogen limited lakes for which data were presented in this report were eutrophic, indicating that nitrogen limitation does not generally occur until a lake system is highly enriched with nutrients. Exceptions to this rule are known (e.g., Lake Tahoe).

11. Because of the variability in each lake system and differences in natural phosphorus concentrations in surface waters, it is felt that the numbers suggested in this report can only be presented as guidelines to avoid the occurrence of nuisance bloom conditions. These guidelines combined with a knowledge of background nutrient levels, land use, lake use and lake morphometry could then be used to establish enforceable nutrient criteria on a lake by lake basis.

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APPENDIX A

LAKE CODE	LAKE NAME	MEAN SECCHI	MEAN CLOR-A	MEDIAN TP(YR)	MEDIAN TP(FALL)	AA YIELD	TROPHIC STATE
0910	ZOAR LAKE	74.3333	18.2667	0.0430	0.0430	8.1000	E
0911	LILLINOAH LAKE	146.0000	11.1333	0.0540	0.0540	12.2000	E
0912	SHELTON LAKE	75.5000	10.2500	0.0395	0.0370	2.9000	E
2309	MOOSEHEAD LAKE	148.9524	1.4619	0.0050	0.0090	0.8400	O
2310	RANGELEY LAKE	148.2857	2.4333	0.0070	0.0070	0.4000	O
2311	SEBAGO LAKE	199.8667	1.4867	0.0040	0.0080	0.1000	O
2313	LONG LAKE	103.8750	6.9211	0.0100	0.0120	0.1000	M
2502	HAGER POND	16.6667	190.4666	1.5250	2.4050	248.2000	E
2503	HARRIS POND	29.8000	12.9500	0.0520	0.0700	7.5000	E
26A0	HOLLOWAY RESERVOIR	60.6250	10.6770	0.0570	0.0590	8.5000	E
26A1	CARO RESERVOIR	27.0000	11.9667	0.1000	0.1175	2.7000	E
26A2	BOARDMAN HYDRO POND	136.5000	1.2667	0.0080	0.0060	0.1000	M
2603	ALLEGAN LAKE	29.7778	20.3111	0.1355	0.1115	16.8000	E
2606	BARTON LAKE	43.8333	27.8000	0.0610	0.1275	11.4000	E
2609	BELLEVILLE LAKE	34.7500	28.2625	0.1220	0.1145	21.5000	E
2610	BETSIE LAKE	38.3333	4.5667	0.0265	0.0220	3.5000	E
2617	LAKE CHARLEVOIX	148.7500	3.0083	0.0060	0.0070	0.1000	O
2621	CONSTANTINE RESERVOIR	43.8333	39.3167	0.0480	0.0275	8.7000	E
2629	FORD LAKE	43.8333	14.7333	0.1110	0.1100	14.6000	E
2643	KENT LAKE	45.0000	33.9444	0.0430	0.0420	8.2000	E
2648	LAKE MACATAWA	22.4000	25.6000	0.1590	0.2050	19.6000	E
2649	MANISTEE LAKE	48.6667	6.3167	0.0245	0.0170	1.8000	E
2665	PENTWATER LAKE	69.3333	16.0833	0.0270	0.0270	4.9000	E
2673	ROSS RESERVOIR	34.6667	10.3833	0.0350	0.0345	8.3000	E
2674	SANFORD LAKE	41.2500	13.7909	0.0180	0.0160	0.9000	E
2683	THORNAPPLE LAKE	57.1667	14.6500	0.0455	0.0430	4.5000	E
2685	UNION LAKE	44.5000	15.6667	0.0470	0.0830	2.7000	E
2688	WHITE LAKE	82.2222	9.2111	0.0265	0.0275	4.5000	E
2693	ST LOUIS RESERVOIR	37.3333	5.5833	0.2060	0.1200	25.4000	E
2694	CRYSTAL LAKE	120.0000	2.9857	0.0090	0.0090	0.1000	M
2696	HOUGHTON LAKE	79.1667	9.2167	0.0160	0.0180	0.2000	M
2697	THOMPSON LAKE	92.1111	11.9667	0.0410	0.0420	2.9000	E
2698	PERE MARQUETTE LAKE	51.3333	11.8333	0.0300	0.0340	5.5000	E
27A1	WINONA LAKE	20.8333	58.5500	0.1070	0.1100	16.6000	E
27A5	ZUMBRO LAKE	59.0000	12.4667	0.4015	0.3100	47.3000	E
27A7	ST CROIX LAKE	43.6667	10.2444	0.0550	0.0300	3.4000	E
2782	GREEN LAKE	109.8333	4.8667	0.0150	0.0160	1.3000	M
2784	DARLING LAKE	100.6667	11.8333	0.0170	0.0170	0.8000	E
2785	LE HOMME DIEU	91.1111	12.4444	0.0195	0.0160	0.2000	E
2789	LAKE CARLOS	111.7500	4.6333	0.0130	0.0130	0.9000	M
27C3	COTTONWOOD LAKE	13.5000	135.5249	0.0875	0.0820	7.7000	E
2705	BARTLETT LAKE	20.0000	49.4667	0.1365	0.1170	10.0000	E
2706	BEAR LAKE	11.0000	61.2333	0.1760	0.0660	2.0000	E
2711	BLACKDUCK LAKE	67.6667	14.5500	0.0430	0.0300	2.1000	E
2750	MADISON LAKE	33.8333	30.8000	0.6505	0.0450	3.8000	E
2752	MALMEDAL LAKE	14.5000	41.0000	0.1250	0.0625	7.4000	E
2760	LAKE MINNETONKA	54.1667	16.5791	0.0470	0.0560	2.1000	E
2786	SUPERIOR BAY	22.3333	6.2000	0.0790	0.0515	2.3000	E
3305	GLENN LAKE	65.5000	3.7833	0.0240	0.0400	0.1000	E
3306	KELLY FALLS POND	69.6667	7.0333	0.0205	0.0350	0.6000	E
3604	CANANDAIGUA LAKE	176.7500	4.3333	0.0090	0.0070	0.1000	O
3606	CARRY FALLS RESERVOIR	88.8333	3.0667	0.0100	0.0110	0.2000	M
3607	CASSADAGA LAKE	101.3333	9.7000	0.0260	0.0320	4.4000	E
360A	LAKE CAYUGA	111.6364	3.2364	0.0145	0.0090	0.1000	M
3611	CROSS LAKE	53.3333	19.4667	0.0765	0.0730	3.2000	E
3613	GOODYEAR LAKE	74.0000	7.4500	0.0260	0.0310	0.3000	E

LAKE CODE	LAKE NAME	MEAN SECCHI	MEAN CLOR-A	MEDIAN TP(YR)	MEDIAN TP(FALL)	AA YIELD	TROPHIC STATE
3615	HUNTINGTON LAKE	138.0000	6.4000	0.0150	0.0150	2.1000	E
3617	KEUKA LAKE	140.6667	5.6500	0.0080	0.0080	0.5000	M
3619	LONG LAKE	116.1667	3.4667	0.0080	0.0080	0.1000	O
3625	OTTER LAKE	45.0000	13.3333	0.0430	0.0440	1.0000	E
3627	OWASCO LAKE	106.4000	8.5333	0.0090	0.0080	0.2000	M
3629	RAQUETTE POND	87.0000	1.8500	0.0100	0.0155	0.2000	M
3630	ROUND LAKE	46.0000	28.3333	0.0765	0.0820	18.4000	E
3632	SACANDAGA RESERVOIR	139.2222	4.8500	0.0090	0.0090	0.1000	M
3634	SCHROON LAKE	147.0000	2.0833	0.0040	0.0040	0.1000	O
3635	SENECA LAKE	157.1250	6.0667	0.0100	0.0080	0.1000	O
3637	SWINGING BRIDGE RESERVOI	51.3333	28.6667	0.0570	0.0310	13.0000	E
3640	LOWER ST REGIS	76.5000	13.3833	0.0170	0.0225	0.6000	E
3641	ALLEGHENY RESERVOIR	51.3333	12.6000	0.0250	0.0530	10.4000	E
4402	SLATERSVILLE RESERVOIR	53.0000	8.1000	0.0340	0.0325	0.1000	E
5001	CHAMPLAIN LAKE	91.5366	11.0609	0.0180	0.0160	1.4000	M
5002	CLYDE POND	67.6667	7.5000	0.0210	0.0210	0.2000	E
5005	HARRIMAN RESERVOIR	111.0000	1.7667	0.0095	0.0080	0.1000	M
5007	LAMOILLE LAKE	58.6667	3.5400	0.0180	0.0190	1.9000	E
5010	LAKE ARROWHEAD	63.0000	8.4833	0.0150	0.0170	0.2000	E
5011	WATERBURY RESERVOIR	94.1667	5.2400	0.0070	0.0060	0.1000	M
5510	CASTLE ROCK FLOWAGE	30.1111	25.4555	0.0620	0.0480	1.7000	E
5532	OCONOMOWOC LAKE	114.6667	3.0667	0.0120	0.0140	0.2000	E
5534	PETENWELL FLOWAGE	27.8889	17.6000	0.0640	0.0540	3.4000	E
5535	PIGEON LAKE	34.6667	5.0000	0.0590	0.0465	12.9000	E
5546	TAINTER LAKE	54.5555	13.6667	0.1110	0.0990	16.8000	E
5550	WAPOGASSET LAKE	71.0000	16.6000	0.0435	0.0390	5.5000	E
5551	LAKE WAUSAU	28.6667	5.0000	0.0595	0.0410	1.5000	E
5555	WISCONSIN LAKE	31.7778	51.3666	0.0580	0.0555	12.0000	E
5559	OKAUCHEE LAKE	75.2000	8.3500	0.0160	0.0165	3.5000	E
5560	BROWNS LAKE	79.3333	6.4000	0.0220	0.0220	0.8000	E
5562	LAKE COMO	20.3333	36.4000	0.0480	0.0340	0.3000	E
5563	LAC LA BELLE	80.3333	7.9333	0.0130	0.0140	0.2000	E
5564	ROCK LAKE	91.3333	8.1333	0.0130	0.0170	0.3000	E
5565	BIG EAU PLEINE RESERVOIR	32.0000	35.4666	0.0710	0.0795	15.2000	E
5566	ROUND LAKE	133.6667	3.5333	0.0110	0.0100	0.2000	E
5569	MIDDLE LAKE	141.3333	4.7333	0.0110	0.0125	0.2000	E
5570	GRAND LAKE	22.4000	65.3199	0.1900	0.0920	13.8000	E
5571	CRYSTAL LAKE	316.0000	1.5000	0.0070	0.0070	0.2000	O
5572	TROUT LAKE	162.0000	2.6833	0.0090	0.0090	0.7000	M
5573	LONG LAKE	34.8333	7.0500	0.0395	0.0370	0.1000	E
5575	ELK LAKE	36.6667	7.1333	0.0380	0.0330	2.8000	E
5581	SUPERIOR BAY	26.0000	15.8000	0.0605	0.0515	2.3000	E

APPENDIX B

DATA FOR FIGURE 5

Storet #	Lake Name & (Trophic State)	Mean depth (m)/ Retention Time (yrs)	P Loading ($g/m^2/yr$)
3302	Powder Mill Pond (E)	133.3	3.25
3303	Winnipesaukee (O)	3.3	0.013
3306	Glenn (E)	850.0	26.42
4402	Slatersville (E)	171.4	4.69
2503	Harris Pond (E)	142.0	11.10
2306	Long (M)	8.7	0.14
2308	Mattawamkeag (M)	33.6	0.60
2309	Moosehead (O)	5.5	0.08
2310	Rangeley (O)	5.1	0.09
2313	Long (M)	4.2	0.12
2314	Bay of Naples (O)	60.0	0.052
5519	Green (M)	1.5	0.92
5539	Shawano (E)	2.1	0.07
5551	Wausau (E)	450.0	28.68
5570	Grand (E)	40.0	8.70
5573	Long (E)	82.9	4.44
5574	Willow (E)	14.1	0.47
5575	Elk (E)	360.0	18.39
5002	Clyde Pond (E)	340.0	7.09
5007	Lamoille (E)	566.7	22.87
5008	Memphremagog (E)	9.1	0.46
5010	Arrowhead (E)	320.0	10.55
5011	Waterbury (M)	56.4	1.23

DATA FOR FIGURE 5
(Page 2)

Storet #	Lake Name & (Trophic State)	Mean depth (m)/ Retention Time (yrs)	P Loading ($g/m^2/yr$)
3609	Champlain (M)	7.5	0.52
2606	Barton (E)	27.7	21.80
2617	Charlevoix (O)	5.23	0.12
2618	Chemung (E)	2.03	0.22
2629	Ford (E)	109.0	5.29
2648	Macatawa (E)	19.9	6.35
2674	Sanford (E)	119.6	3.91
2683	Thornapple (E)	142.3	9.29
2685	Union (E)	182.0	9.27
2696	Houghton (M)	1.78	0.05
27B2	Green (M)	1.73	0.09
27B5	Le Homme Dieu (E)	0.81	0.12
27B9	Carlos (M)	3.54	0.14
3604	Canandaigua (O)	2.6	0.013
3608	Cayuga (M)	4.81	0.058
3634	Schroon (O)	34.1	0.39
3637	Swinging Bridge (E)	53.4	7.07
3605	Cannonsville (E)	33.4	4.26
2311	Sebago (O)	5.7	0.08

O - Oligotrophic
M - Mesotrophic
E - Eutrophic

DATA FOR FIGURES 6 and 7

All Lakes Eutrophic and Nitrogen Limited

Storet #	Lake Name	Mean Depth/Ret'n Time (meters/years)	P Loading ($g/m^2/yr$)	N Loading ($g/m^2/yr$)
0901	Aspinook Pond	85.5	8.4	94.9
0903	Community Lake	244.0	337.0	1,742.0
0905	Hanover Pond	685.0	228.9	1,405.0
0911	Lillinoah	337.0	24.9	335.2
0910	Zoar	535.0	41.3	723.8
3305	Kelley's Falls Pond	575.0	17.79	525.6
4403	Turner Reservoir	75.0	58.59	216.9
2304	Estes	100.0	9.65	110.29
2312	Sebasticook	11.1	0.68	16.3
5502	Altoona	150.0	20.6	224.7
5503	Beaver Dam	3.57	0.9	10.1
5508	Butte Des Morts	90.0	9.60	181.1
5509	Butternut	10.5	0.64	13.9
5513	Delavan	2.5	1.1	8.7
5515	Eau Claire	77.8	9.0	119.6
5520	Kegonsa	13.7	1.85	27.9
5522	Koshkonong	22.7	9.87	72.4
5531	Nagawicka	6.7	1.33	24.1
5535	Pigeon	75.0	6.45	160.2
5538	Poygan	52.5	5.55	94.2

DATA FOR FIGURES 6 and 7
(Page 2)

Storet #	Lake Name	Mean Depth/Ret'n Time (meters/years)	P Loading ($g/m^2/yr$)	N Loading ($g/m^2/yr$)
5545	Swan	19.8	2.78	39.5
5546	Tainter	376.7	19.61	223.4
5548	Townline	5.4	1.39	9.4
5550	Wapogasset	9.8	0.71	11.1
5554	Winnebago	7.0	8.35	134.0
5555	Wisconsin	180.0	15.0	246.8
5556	Wissota	152.0	7.64	219.9
5559	Tichigan	34.6	20.51	91.2
5565	Big Eau Pleine	350.0	1.52	22.98
5577	Beaver Dam	107.1	0.88	10.1
5541	Sinissippi	26.6	6.35	62.1
2603	Allegan	176.3	31.3	403.4
2609	Belleville	88.4	15.73	217.1
2631	Fremont	5.29	2.97	16.4
2640	Jordan	8.79	1.14	29.3
2643	Kent	22.8	1.60	22.7
2659	Muskegon	111.3	6.81	109.5
2671	Randall Lake	48.9	4.0	123.4
2688	White	43.85	2.08	53.9
2691	Mona	18.9	5.97	49.8
2692	Long	61.6	4.62	86.8
2699	Strawberry	186.9	9.18	224.8

DATA FOR FIGURES 6 and 7
(Page 3)

Storet #	Lake Name	Mean Depth/Ret'n Time (meters/years)	P Loading ($g/m^2/yr$)	N Loading ($g/m^2/yr$)
27A1	Winona	0.92	1.65	6.9
27A2	Wolf	85.30	6.43	60.3
27B1	Wagonga	0.92	4.0	16.0
27B3	Nest	8.83	0.79	16.4
27C0	Andrusia	61.2	4.02	59.1
27C1	Bemidji	13.3	0.44	13.4
2702	Albert Lea	5.50	6.31	61.2
2704	Badger	4.05	0.63	10.6
2711	Blackduck	1.07	0.14	2.6
2719	Cokato	6.74	2.6	27.4
2725	Elbow	3.87	7.89	31.2
2731	Fanny	9.68	15.0	30.6
2752	Malmedal	1.38	0.27	4.79
2757	McQuade	17.30	1.2	36.5
2765	Pelican	0.73	0.06	2.0
2777	Sakatah	17.36	3.74	57.7
2782	Silver	0.54	0.075	4.2
2793	Trout	0.87	0.33	2.8
2783	Sixmile	17.9	6.28	49.78

DATA FOR FIGURES 6 and 7
(Page 4)

Storet #	Lake Name	Mean Depth/Ret'n Time (meters/years)	P Loading ($g/m^2/yr$)	N Loading ($g/m^2/yr$)
3610	Chautauqua	4.89	0.34	5.56
3611	Cross	288.4	33.7	504.6
3633	Saratoga	16.0	1.26	18.9